Fast Tracking Emerging Technology Development for Space Exploration
A Carbon Nanotube Example

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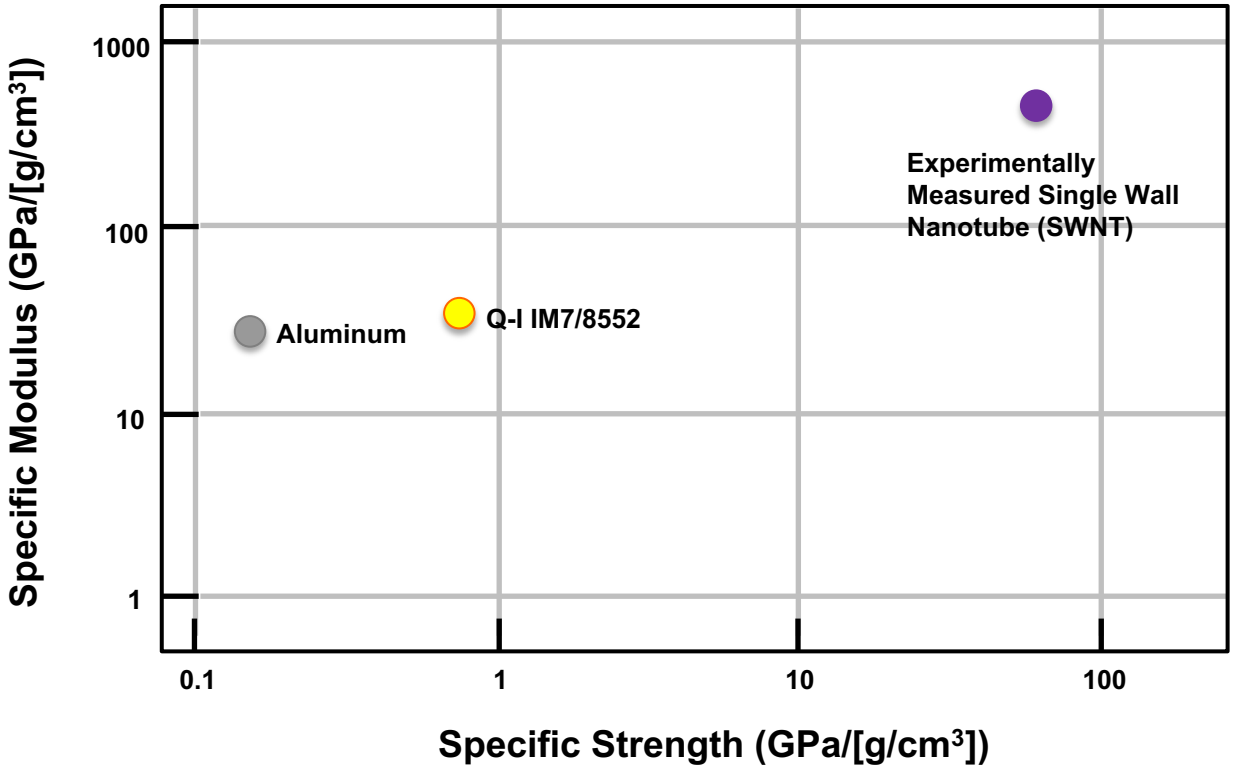
Motivation



Harris, C. E. et al., NASA TM 211664, 2002.

Motivation

Summary of the Problem

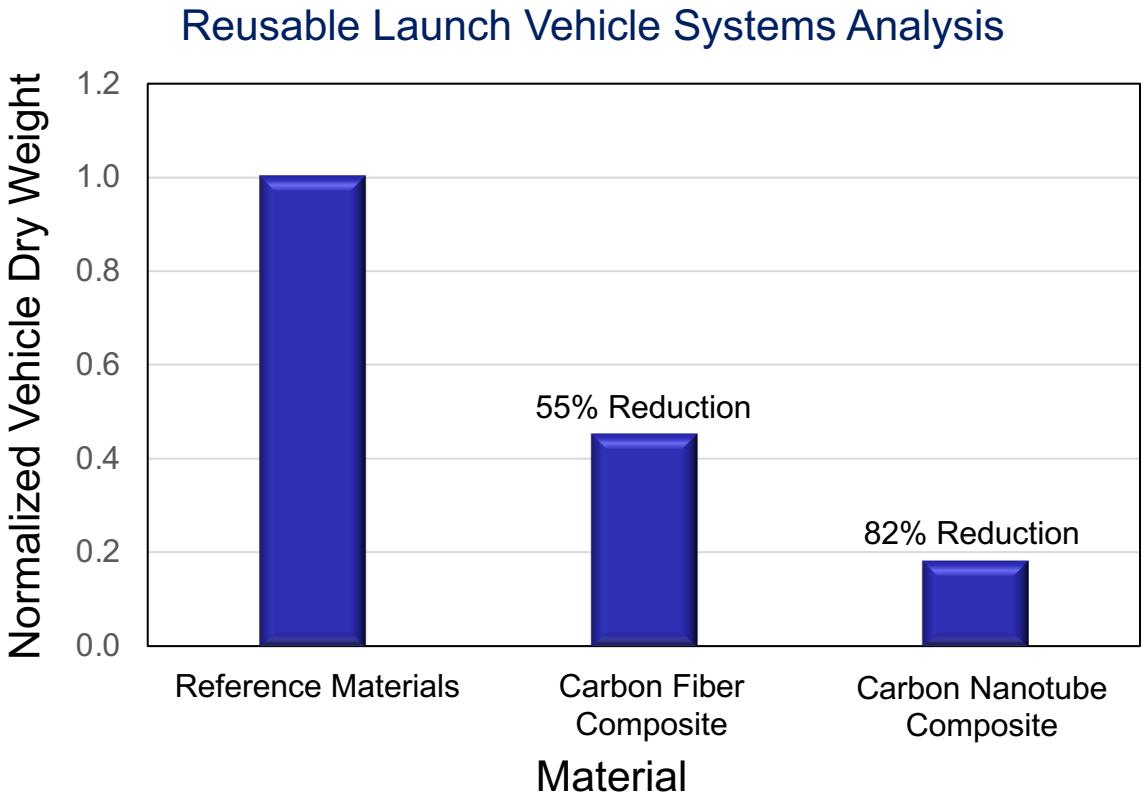
- Cost increases in proportion to the mass ratio.
- Mass ratio increases linearly with the dry mass and exponentially with Δv.
- Reducing structural mass reduces mission cost at constant payload or increases mission capability at constant cost.

	Mass Ratio*	Cost per pound*
Low Earth Orbit	20	$4,000
Earth to Moon	200	$40,000
To Moon, Return to Earth	500	$100,000
Earth to Mars	500	$100,000
To Mars, Return to Earth	5000	$1,000,000

*Gordon, G. D., AIAA SPACE 2007, paper 6278.

Motivation

Reusable Launch Vehicle Systems Analysis Model



Harris, C. E. et al., NASA TM 211664, 2002.

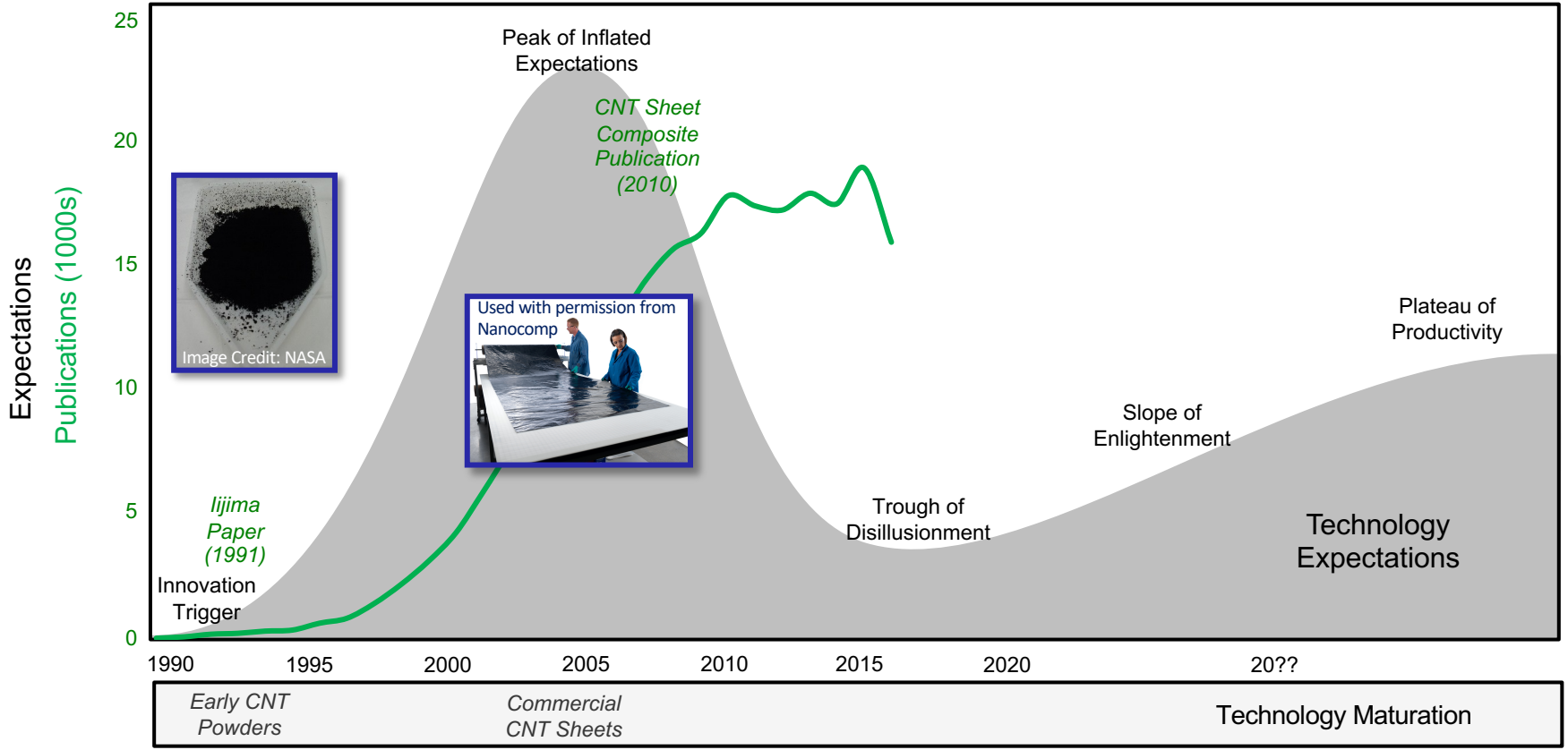
Technology Development Approaches

- Technology Push
- Technology Pull
- Technology Pull Guided Technology Push

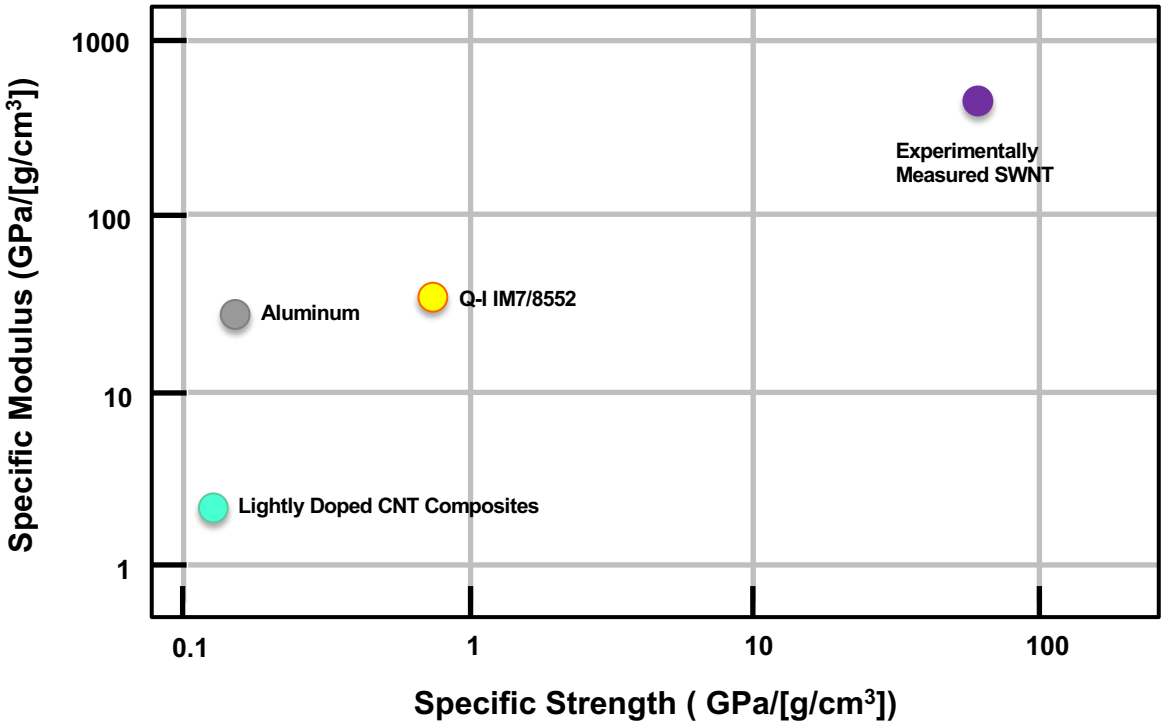
Technology Push

- New/Different
- Immature
- Hyped
- Potentially disruptive
- Can spur significant basic research investments

Carbon Nanotube (CNT) Gartner Hype Cycle



Outcomes



Lessons Learned

- Analogous to very short chopped fiber composites
- Limited by material supply and quality
- Very low volume fraction (<5%)
- Limited improvement over matrix mechanical properties
- Payoffs noted in electrical/multifunctional properties
- Output: Papers, presentations, patents
- Structural applications envisioned did not materialize

- Representative data point from Siochi, E. J. et al., MRS Bulletin, **40**, 829-835, 2015.

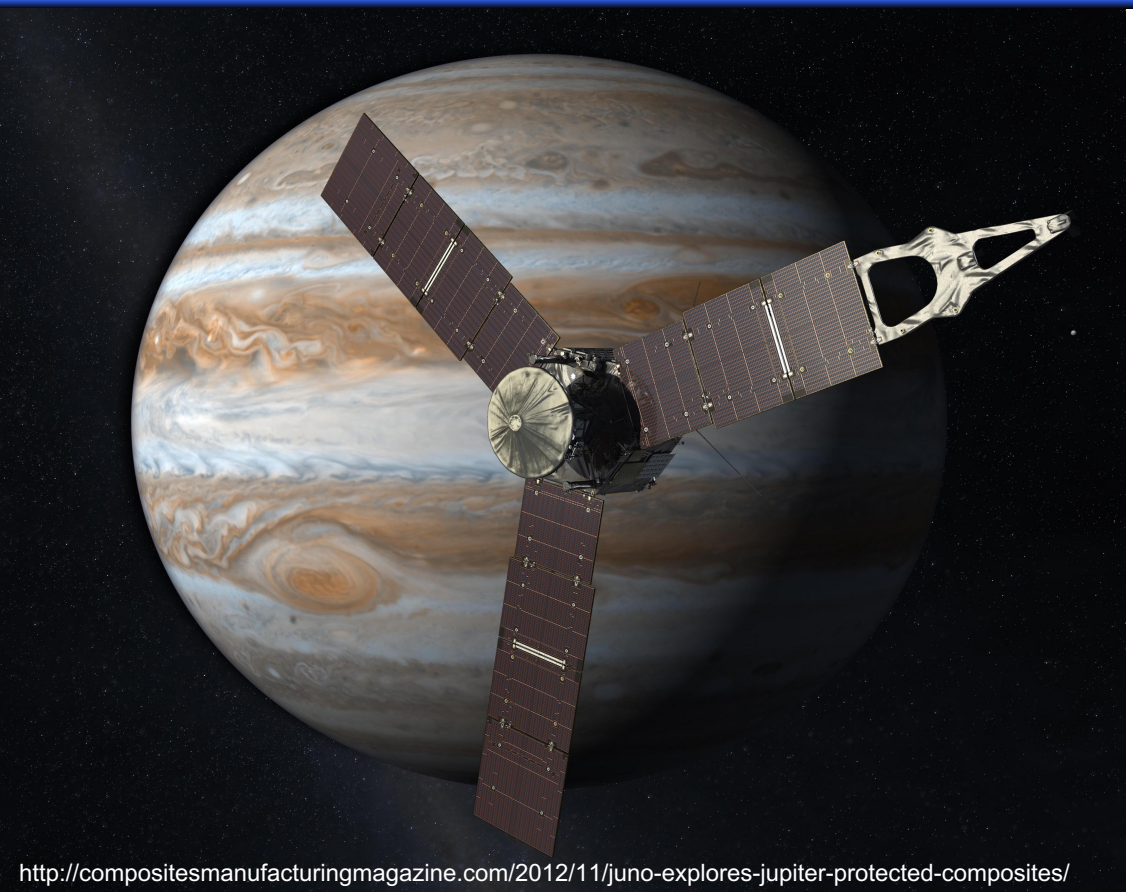
Technology Development Approaches

- Technology Push
- **Technology Pull**
- Technology Pull Guided Technology Push

Technology Pull

- Performance needs identified
- Schedule driven
- Solution space defined by what is ready for insertion
- Typically risk averse

Carbon Nanotubes on Juno Spacecraft



http://compositesmanufacturingmagazine.com/2012/11/juno-explores-jupiter-protected-composites/

Composites and carbon nanotubes were implemented in four components on the Juno spacecraft: the rocket engine tubes, the engine cover and the outside and inside face sheets.

Outcomes

Lessons Learned

- Emerging technology can be implemented if it meets a performance requirement for which there is no other existing solution.
- Technology must be evaluated for the required function.
- Technology must be ready to insert on schedule.
- Structural performance objective still not realized, but technology was flown due to other performance benefits.

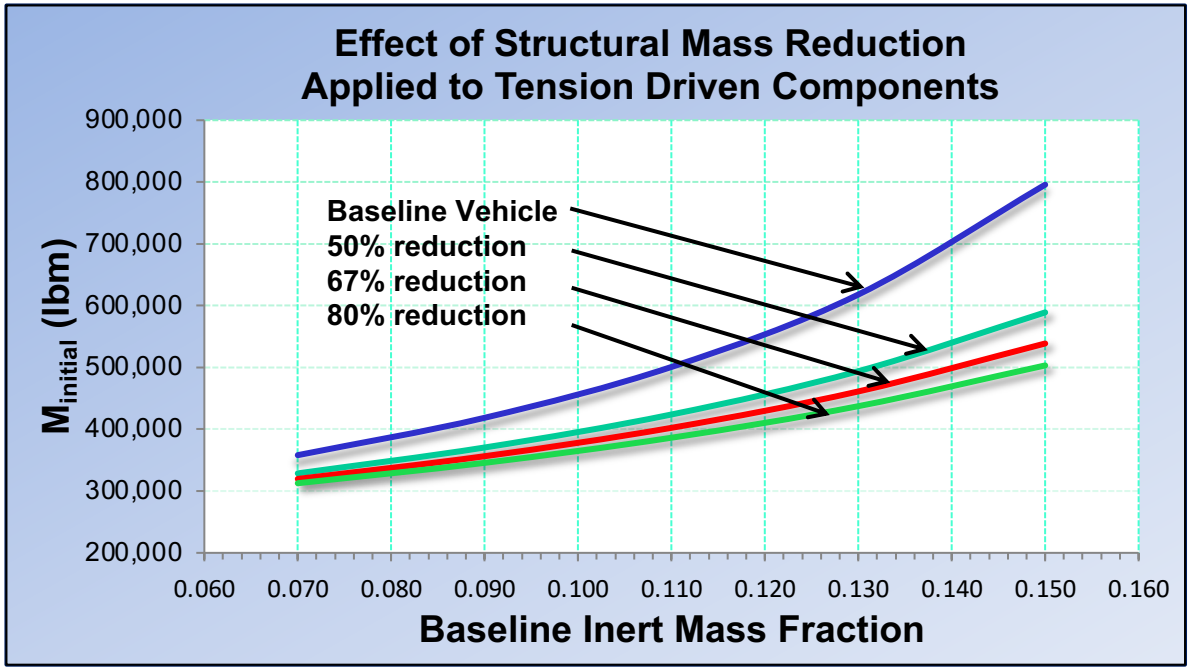
Technology Development Approaches

- Technology Push
- Technology Pull
- **Technology Pull Guided Technology Push**

Technology Pull Guided Technology Push

- Use-driven fundamental research
- Considers systems level benefits
- From lab to demonstration

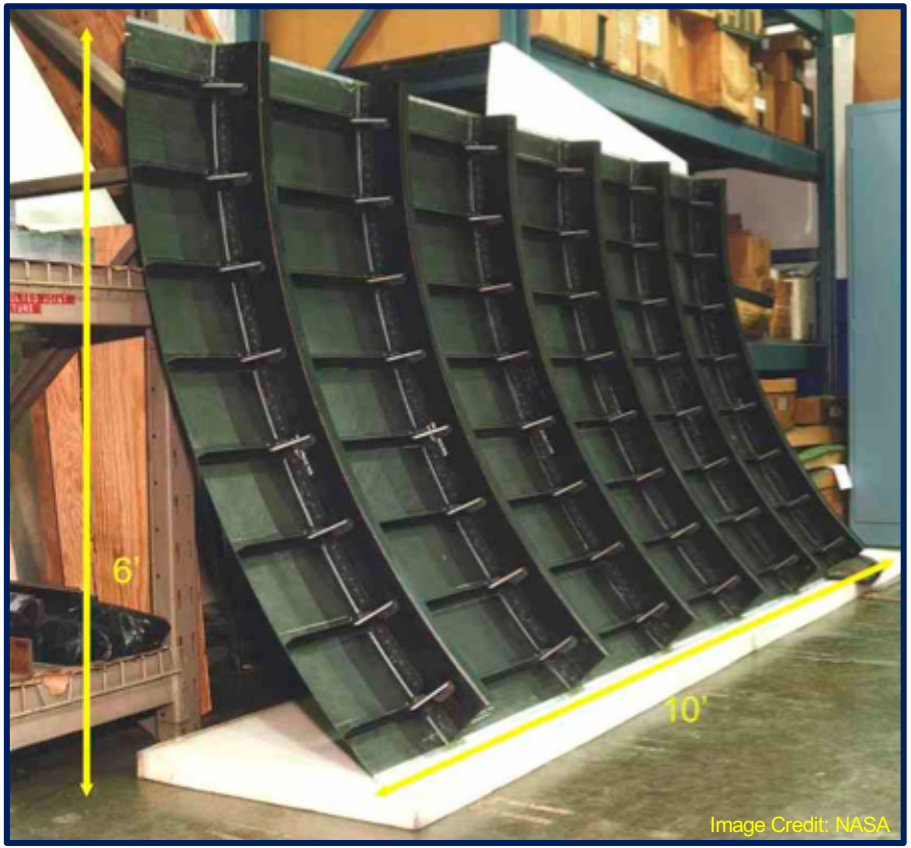
Setting Goals using Systems Analysis



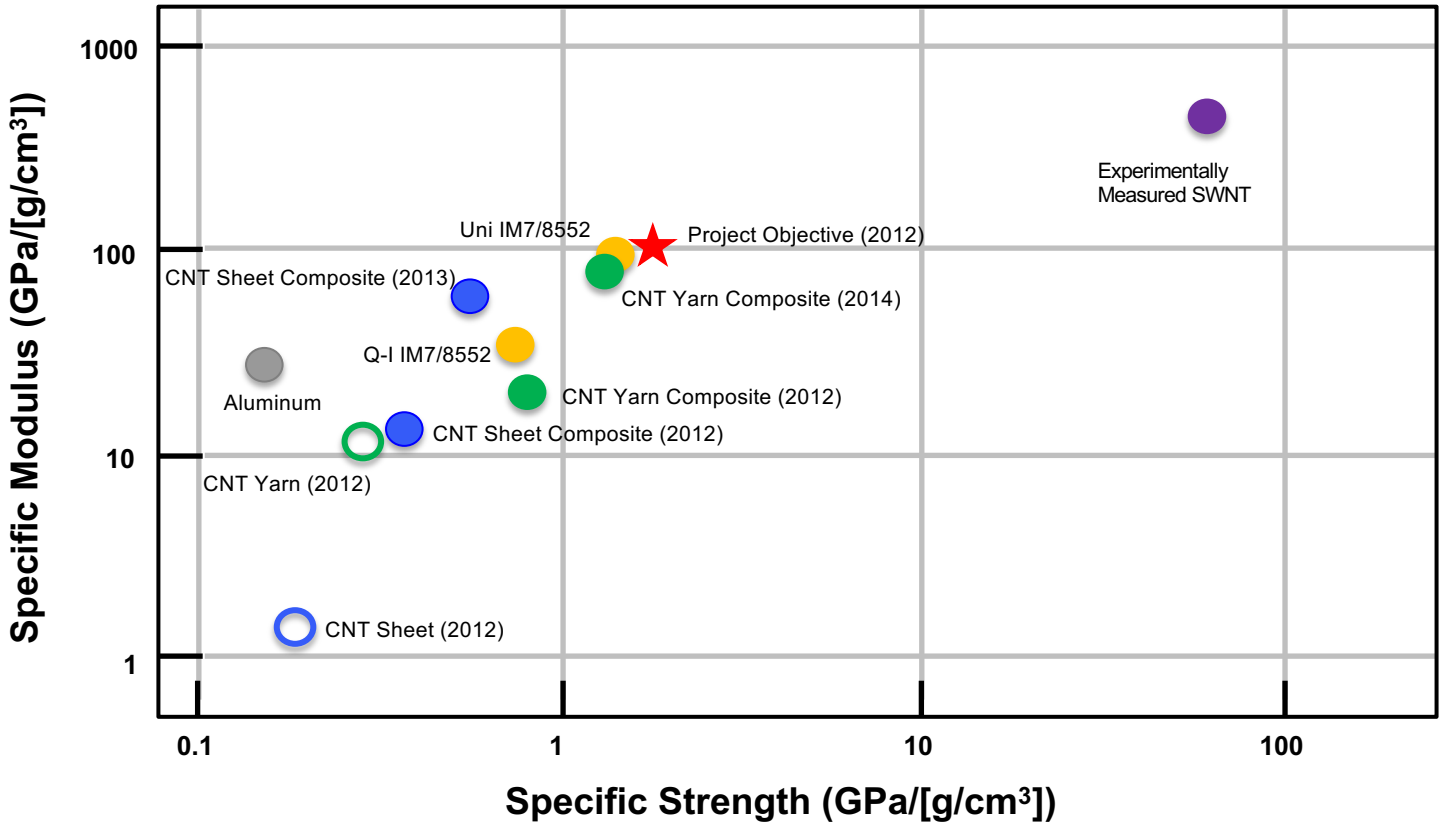
- A 2-3x improvement in specific mechanical properties will permit substantial mass reduction in structural and non-structural components.

McMillan, M., White Paper, March, 2013.

State-of-the-Art Lightweight Structural Material



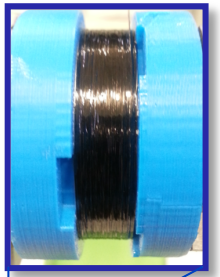
Nano to Macro Challenge

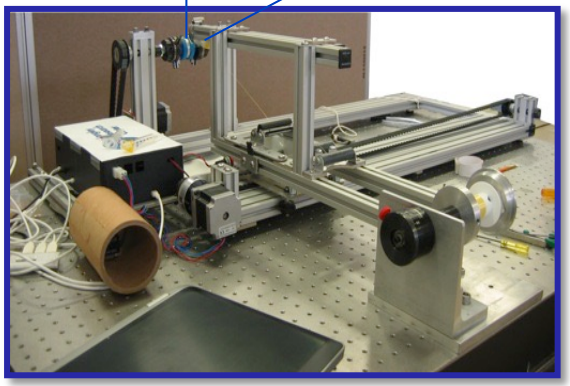


Rapid Prototyping of CNT Composite Fabrication

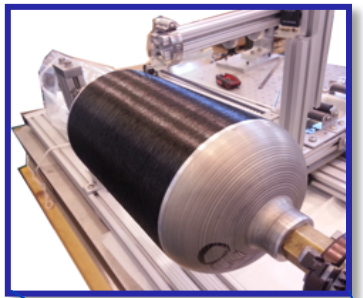
Tabletop Filament Winder for Rapid Prototyping of Composite Processing

Aluminum Ring





CNT Composite Overwrapped Pressure Vessel



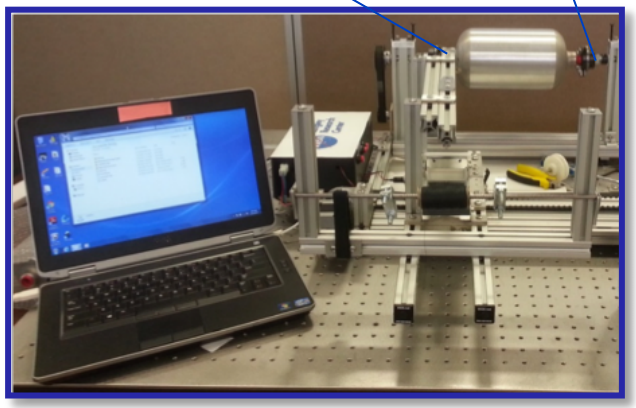
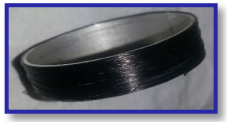
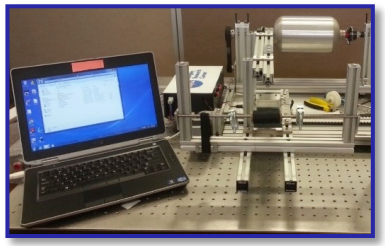


Image Credit: NASA

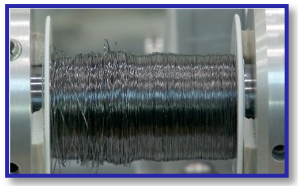
Prototyping to Support Materials Development



CNT Composite Overwrapped Ring

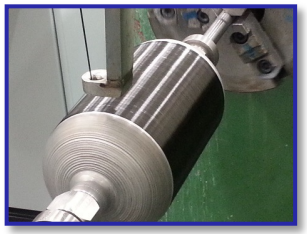


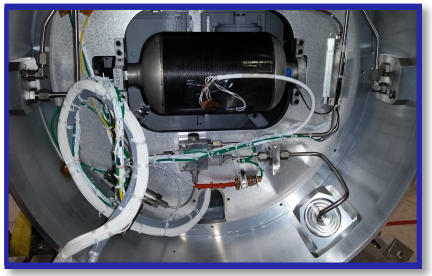
Composite Process Prototyping



High Strength CNT Yarn

Commercial Scale CNT Composite Winding



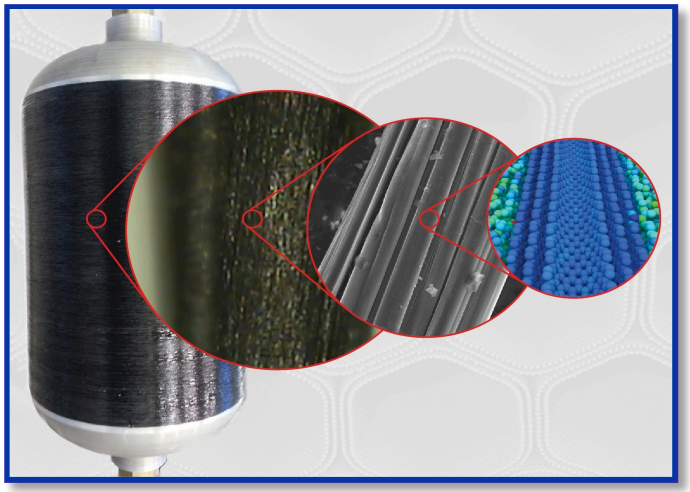


CNT Composite Overwrapped Pressure Vessel Cold Gas Thruster

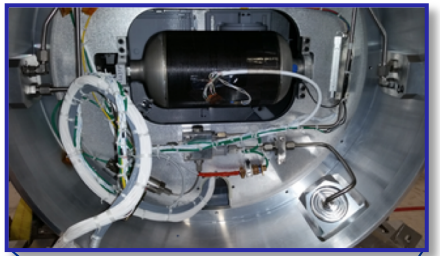
Sounding Rocket Integration

Image Credit: NASA

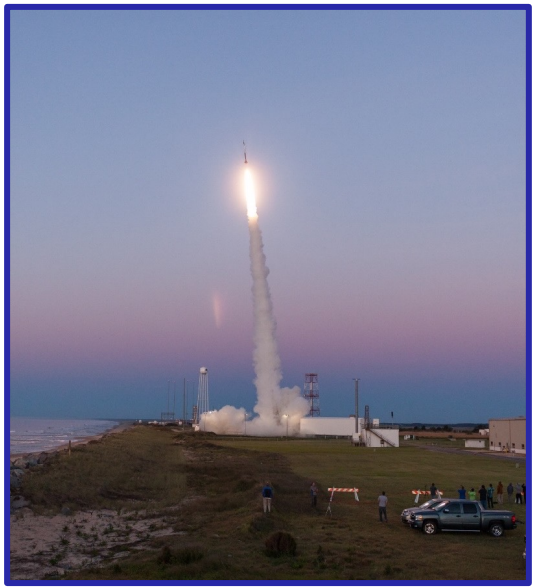
Computationally Guided Use Driven Materials Research



October 2013 – September 2015



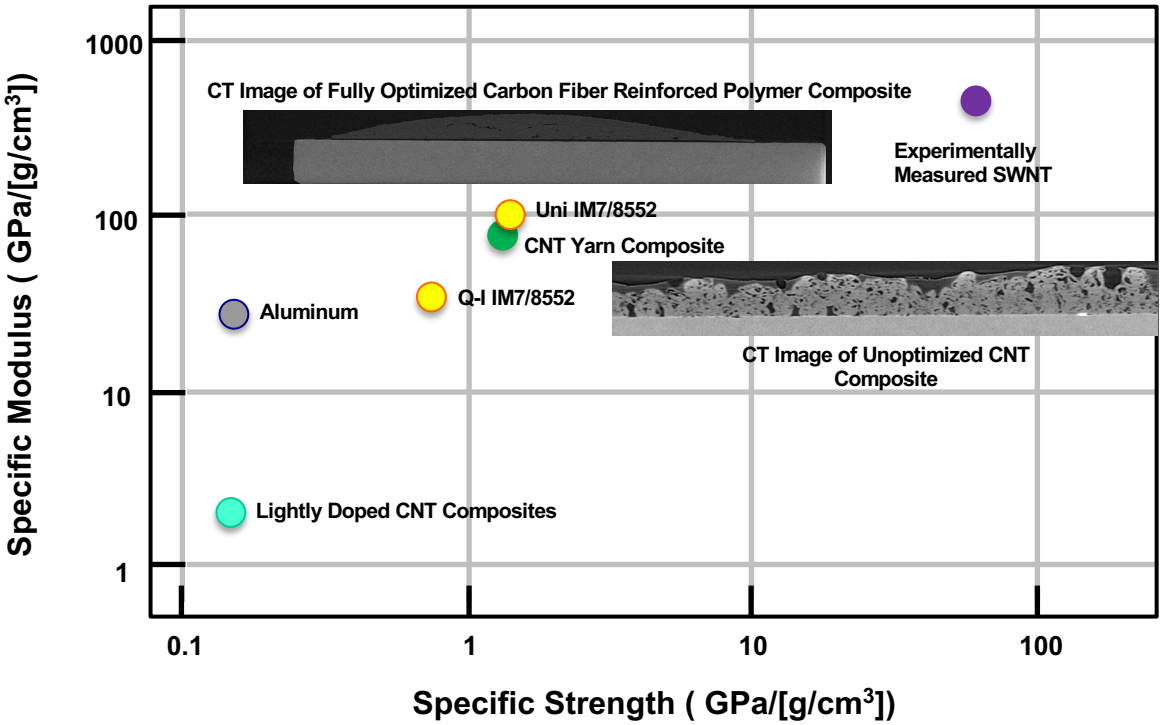
October 2016



May 2017

https://www.nasa.gov/feature/nanotechnology-flight-test-material-impact-on-the-future

Outcomes



Measurable Advancements

- Improvement in mechanical properties
  - Systems level guided, goal focused research.
  - Project objective provided basis for objective decisions.
- Increase in Manufacturing Readiness Level
  - Volume – material available in spool lengths of hundreds of meters.
  - Consistency – materials met A-basis allowable of at least 20 N breaking force.

Image Credit: NASA

Technology Transition Ecosystem

- Displacement of state-of-the-art technologies
  - Performance
  - Scale
  - Schedule
  - Risk
  - Cost
- Decision making for prioritization
  - Systems benefits analysis
  - Clear, quantified metrics for goals

From Publications to Economic Payoff

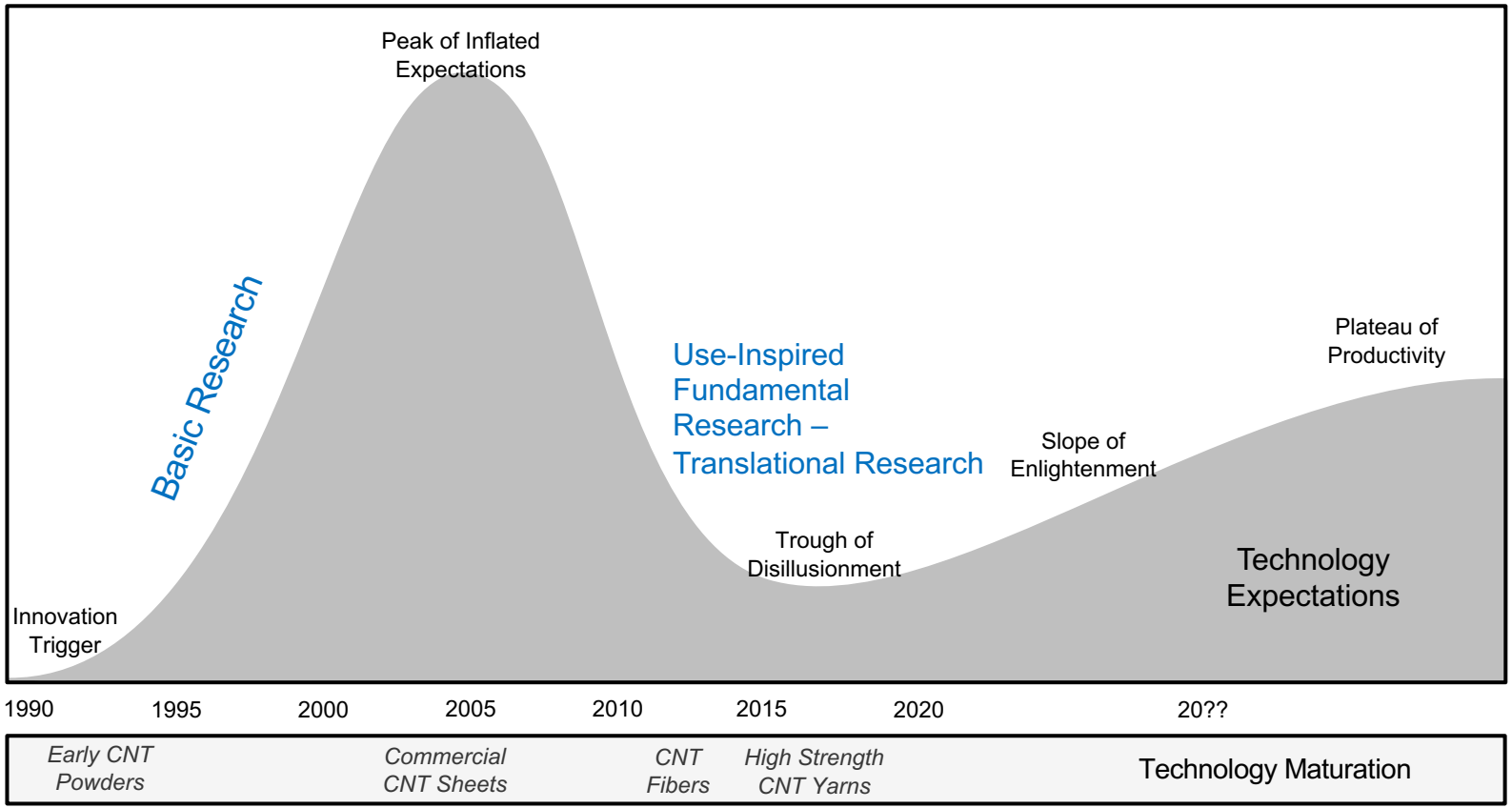
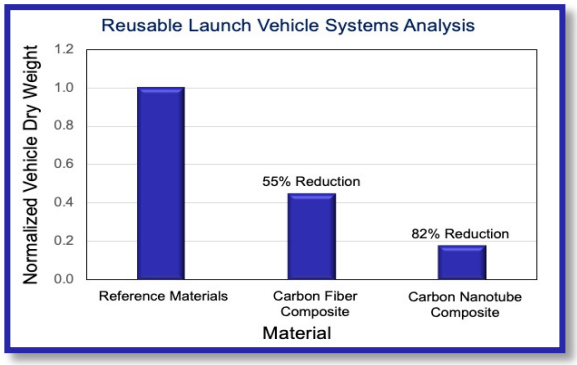
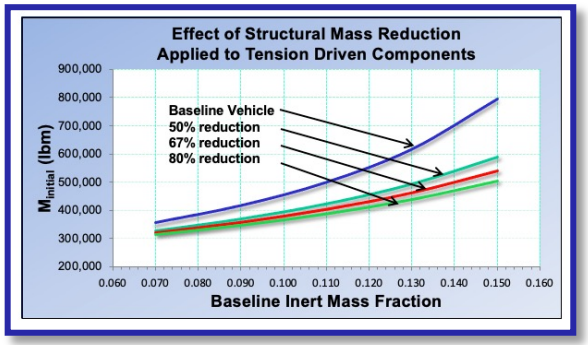


Image Credit: NASA

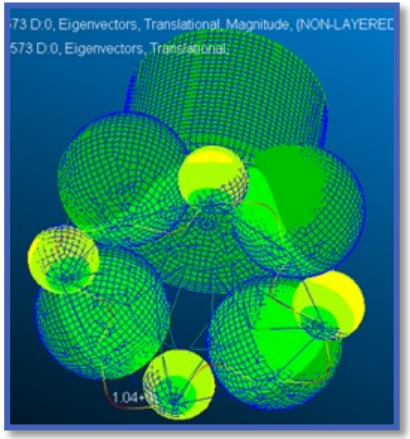
Systems Benefits Guided Technology Maturation



~2001



2010



2021

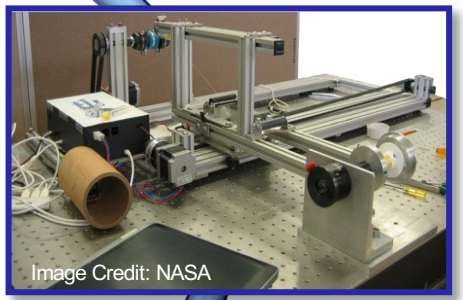
Lessons Learned

- High order systems benefits analysis
  - Useful for advocacy
  - Provides clear performance metrics to evaluate progress
- Higher fidelity systems models
  - Development necessary to provide more detailed guidance on specific component applications
  - Models need to include parameters offered by new technology

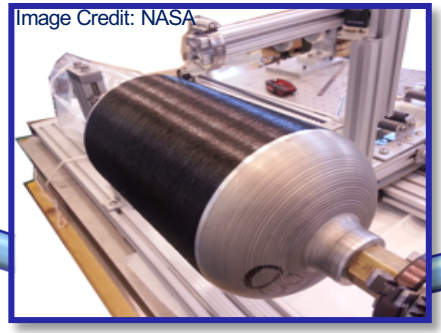
Image Credit: NASA

Rapid Prototyping for Manufacturing Feedback

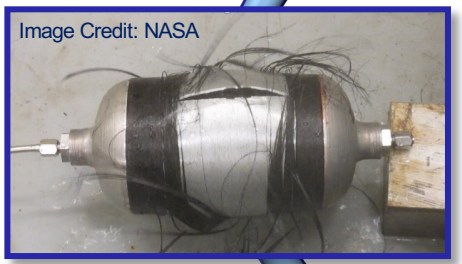
CNT Manufacturing



CNT Composite
Process Development



CNT Composite Manufacturing



CNT Composite Testing

Use Driven Technology Maturation

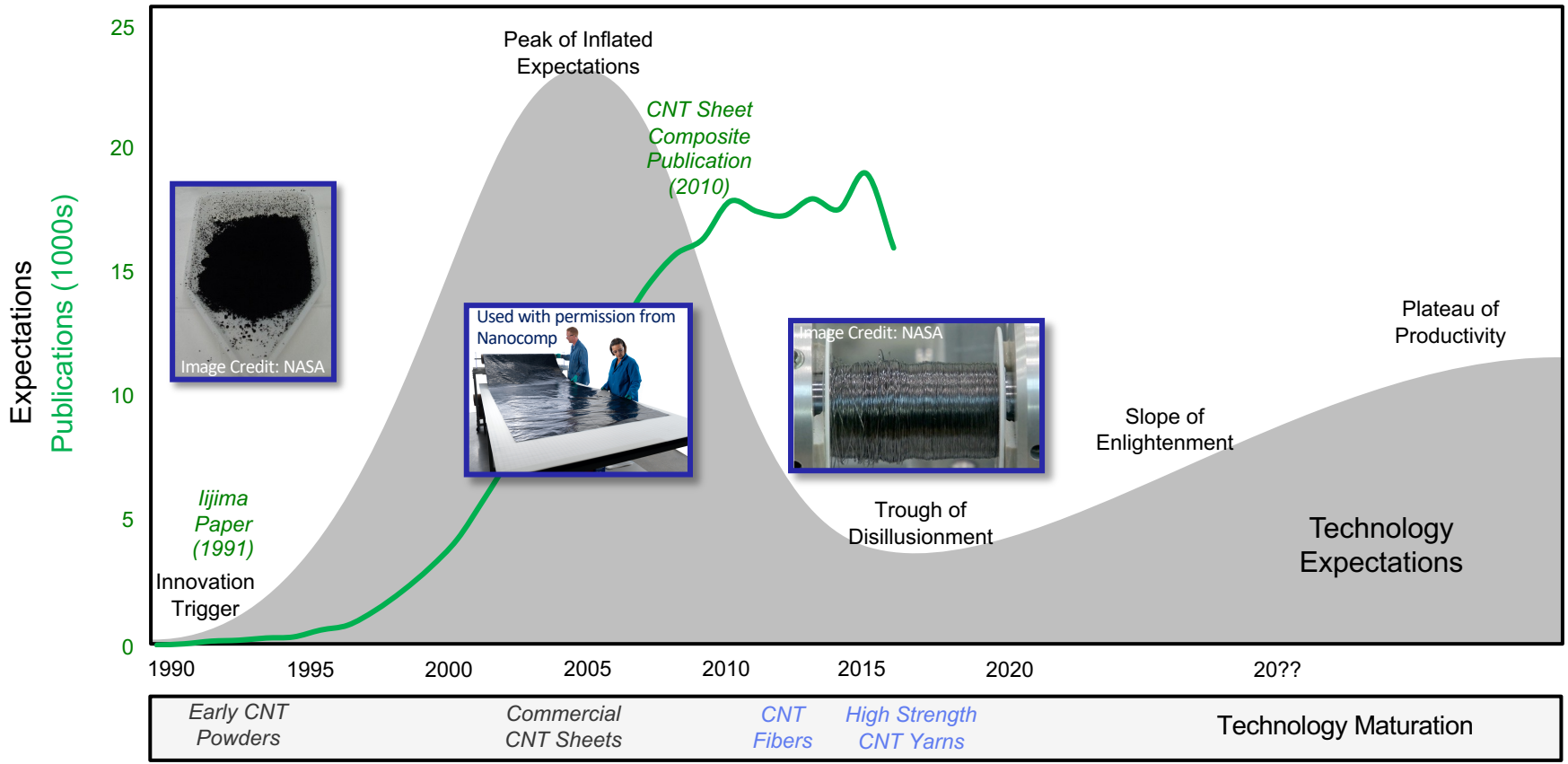


Image Credit: NASA

Systems Defined Goal Provides Common Objective

NASA Centers
- LaRC
- MSFC

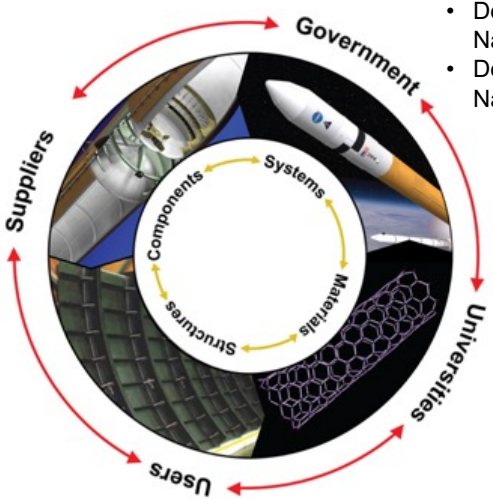
Public/Private Partnerships
- Northrup Grumman
- University of Dayton Research Institute/State of Ohio

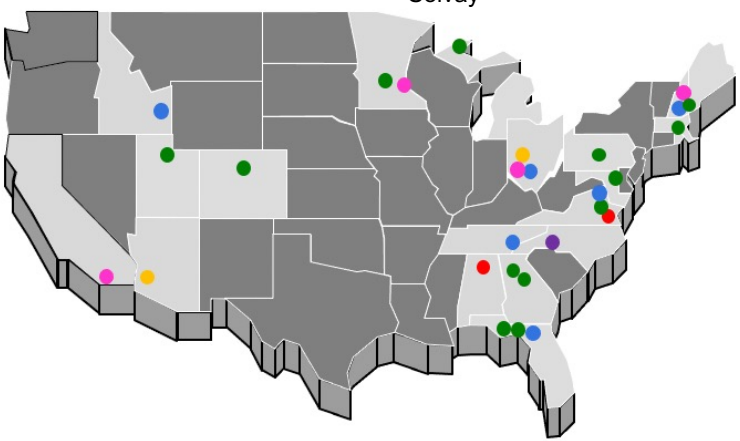
OGA Leveraging
- AFOSR
- AFRL – ManTech Program
- DoD
- DoE - ARPA-E
- DoE – Idaho National Lab
- DoE – Oak Ridge National Lab

Small Business
- Textum, Inc.

SBIR/STTR
- Nanocomp
- Cornerstone Research Group
- Minnesota Wire & Cable
- Applied Composites

NSTRI
- Florida State U
- MIT
- VCU
- Ga Tech
- Penn State U
- FL A&M U
- Solvay
- Michigan Tech
- U of Utah
- U of Colorado
- Johns Hopkins
- U of Minnesota
- Nanocomp





Incentivize multidisciplinary partnerships to accelerate maturation of an emerging material ecosystem.

Image Credit: NASA

Evolution of NASA's Role in the Nanotechnology Landscape

- Early
  - Basic research
  - From structural materials to multifunctional materials
- Current – Technology Transition
  - Evaluating payoff from investments
    - Metrics from systems level benefits
    - Define structural applications
    - Acknowledge realities of technology insertion
  - Integration of new tools – computational materials, 3D printing, machine learning
  - Bridging academia and industry
  - Publications are not a sufficient measure of payoff.
- Lessons learned and steps forward
  - Challenges of collaborations between academia and industry for national benefit
  - Collaboration and coordination efforts across funding agencies would benefit from opportunities for technology transition pull, including from major industry users.
  - Technology insertion is based on performance and value.

Provide technology pull as a means of demonstrating measurable technology maturation

Technology pull can guide accelerated maturation of emerging technologies.

Image Credit: NASA